

Agricultural Sustainability in Indonesia: The Role of Energy, Technology, Markets, and Institutions

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ABSTRACT

This study investigates the transformation of environmentally friendly agriculture in Indonesia by analyzing the impact of renewable energy use, precision agriculture technology, market access, and institutional support on agricultural sustainability outcomes. A quantitative approach was employed using primary data collected from 85 respondents through a structured questionnaire measured on a five-point Likert scale. Data were analyzed using Structural Equation Modeling with Partial Least Squares (SEM-PLS 4) to examine both direct and indirect relationships among variables. The results indicate that renewable energy use, precision agriculture technology, market access, and institutional support all have significant positive effects on sustainability outcomes. Institutional support also shows strong influence on the adoption of renewable energy and precision agriculture. Furthermore, market access partially mediates the relationship between technological adoption and sustainability outcomes. The model demonstrates strong explanatory power, indicating that the integration of technological, economic, and institutional factors plays a crucial role in driving sustainable agricultural transformation. This study provides practical implications for policymakers and stakeholders in designing integrated strategies to enhance agricultural sustainability in Indonesia.

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1. INTRODUCTION

Agriculture remains a cornerstone of Indonesia's economy, playing a vital role in employment generation, food security, and rural development. As one of the world's most biodiverse countries with extensive agroecological diversity, Indonesia has historically relied on agriculture as a strategic pillar for national growth [1], [2]. However, the persistence of conventional agricultural practices characterized by excessive chemical inputs, inefficient energy consumption, and

limited technological integration has increasingly raised concerns regarding environmental degradation, declining soil fertility, greenhouse gas emissions, and long-term productivity sustainability [3], [4]. These structural challenges underline the urgency of transitioning toward environmentally sustainable agricultural systems that simultaneously address ecological integrity, economic viability, and social welfare.

In response to these challenges, the paradigm of environmentally friendly

agriculture has gained increasing attention in both policy and academic discourse. This approach emphasizes the adoption of practices that minimize environmental harm while maintaining or enhancing agricultural productivity. Central to this transformation is the integration of renewable energy sources, such as solar-powered irrigation systems and bioenergy utilization, which contribute to reducing carbon emissions and dependence on fossil fuels [5], [6]. Concurrently, the emergence of precision agriculture technologies including sensors, drones, and data-driven decision-support systems has enabled more efficient resource allocation, improved crop management, and enhanced productivity [7], [8]. These innovations represent a fundamental shift from traditional experience-based farming toward a data-driven, technology-enabled agricultural system.

Nevertheless, the transition toward sustainable agriculture cannot be understood solely through a technological lens. Market access plays a crucial role in determining whether farmers can translate sustainable practices into tangible economic benefits [9], [10]. Structural constraints such as fragmented supply chains, price volatility, and limited access to distribution networks often restrict farmers' ability to capture value from environmentally friendly production [11], [12]. Conversely, improved market access facilitated by digital platforms, cooperative systems, and efficient logistics—can create strong economic incentives for adopting sustainable agricultural practices by ensuring stable demand and fair pricing mechanisms [13], [14].

Beyond market mechanisms, institutional support constitutes a critical enabling factor in agricultural transformation. Government policies, extension services, financial incentives, and capacity-building initiatives significantly influence farmers' adoption behavior and their ability to implement sustainable practices [11], [15]. In Indonesia, various policy interventions ranging from renewable energy subsidies to digital agriculture training programs have been introduced to accelerate this transition.

However, the effectiveness of such initiatives remains uneven across regions due to disparities in institutional capacity, governance quality, and stakeholder coordination. This highlights the importance of understanding institutional dynamics as a key driver of sustainability outcomes [11], [16].

Despite the growing body of literature on sustainable agriculture, a significant research gap persists in understanding how technological, economic, and institutional factors interact simultaneously within an integrated framework. Existing studies tend to examine these determinants in isolation, thereby overlooking the complex interdependencies that characterize agricultural transformation processes. Furthermore, empirical studies employing advanced analytical approaches such as Structural Equation Modeling (SEM-PLS) remain limited, particularly in the context of developing countries and small- to medium-scale agricultural actors. This gap is especially relevant for Indonesia, where structural heterogeneity and institutional diversity require a more comprehensive analytical approach.

To address this gap, this study investigates the direct and indirect effects of renewable energy use, precision agriculture technology, market access, and institutional support on agricultural sustainability outcomes. Using a quantitative approach based on data collected from 85 respondents and analyzed through SEM-PLS 4, this research develops and tests an integrated model of environmentally friendly agricultural transformation. By incorporating both direct relationships and mediation effects, this study offers a more nuanced understanding of the mechanisms through which sustainability outcomes are achieved.

This research contributes to the literature in several ways. First, it provides an integrated empirical model that simultaneously examines technological, market, and institutional dimensions of sustainable agriculture. Second, it extends the application of SEM-PLS in the context of agricultural sustainability in developing

economies. Third, it offers practical insights for policymakers and stakeholders by identifying key leverage points for accelerating sustainable agricultural transformation.

Ultimately, this study underscores the necessity of a holistic approach to agricultural development—one that combines technological innovation, renewable energy adoption, market integration, and robust institutional support. Such an integrated framework is essential for building resilient and sustainable agricultural systems capable of addressing the environmental and economic challenges facing Indonesia in the future.

2. LITERATURE REVIEW

2.1 *Theoretical Foundation of Sustainable Agriculture*

Sustainable agriculture is broadly defined as an agricultural system that meets current food and fiber needs without compromising the ability of future generations to meet their own needs, integrating three fundamental dimensions: environmental sustainability, economic viability, and social equity. From a theoretical perspective, it is grounded in sustainable development theory, which emphasizes the balance between ecological preservation and economic growth, as well as the triple bottom line framework, which highlights the importance of achieving environmental, social, and economic performance simultaneously [17]–[19]. In the context of agricultural transformation, the Resource-Based View (RBV) and Technology Adoption Theory provide a strong conceptual foundation, where RBV suggests that access to valuable, rare, and inimitable resources such as

advanced technologies and institutional support can enhance performance [20]–[22], including sustainability outcomes, while Technology Adoption Theory underscores the role of external drivers, such as institutional support and market incentives, alongside internal readiness in shaping the adoption of innovations like renewable energy and precision agriculture [22], [23]. Therefore, the transformation toward environmentally friendly agriculture can be understood as a multidimensional process driven by the interaction of technological, economic, and institutional factors that collectively influence sustainability outcomes.

2.2 *Renewable Energy Use and Agricultural Sustainability*

Renewable energy use in agriculture refers to the adoption of energy sources such as solar, wind, and biomass to support farming activities, where their integration reduces dependence on fossil fuels, lowers greenhouse gas emissions, and contributes to environmental sustainability [24], [25]. The use of solar-powered irrigation systems and bioenergy, for instance, can significantly reduce operational costs while minimizing environmental impact. Empirical studies further indicate that renewable energy adoption enhances both environmental and economic performance by improving energy efficiency and reducing input costs [26], [27]. In developing countries such as Indonesia, renewable energy also plays a crucial role in increasing energy accessibility in rural areas, thereby supporting

agricultural productivity. Based on these arguments, the following hypothesis is proposed:

H1: Renewable energy use has a positive effect on agricultural sustainability outcomes.

2.3 *Precision Agriculture Technology and Sustainability Outcomes*

Precision agriculture refers to the use of advanced technologies such as sensors, drones, GPS systems, and data analytics to optimize agricultural practices, enabling farmers to apply inputs more efficiently, thereby reducing waste and minimizing environmental impact [28], [29]. Theoretically, this approach aligns with the principles of smart farming and digital transformation, which enhance decision-making through real-time data and automation [30], [31]. Empirical evidence demonstrates that precision agriculture improves crop yields, increases resource efficiency, and reduces environmental degradation [31], [32], while also supporting economic sustainability by lowering production costs and increasing profitability. Thus, the following hypothesis is formulated:

H2: Precision agriculture technology has a positive effect on agricultural sustainability outcomes.

2.4 *Market Access and Agricultural Sustainability*

Market access refers to the ability of farmers to sell their products in local, national, or international markets under favorable conditions, including infrastructure, pricing mechanisms, distribution

channels, and access to market information [11], [12]. Improved market access provides strong incentives for farmers to adopt sustainable practices by ensuring better prices and stable demand for environmentally friendly products [33]. In line with market-driven sustainability theory, increasing consumer demand for green products encourages producers to shift toward more sustainable production methods [33], [34]. Furthermore, digital marketplaces and supply chain integration enhance transparency and efficiency, thereby supporting sustainable agricultural practices. Therefore, the following hypothesis is proposed:

H3: Market access has a positive effect on agricultural sustainability outcomes.

2.5 *Institutional Support and Sustainable Agriculture*

Institutional support includes policies, financial assistance, training programs, and extension services provided by governments and related organizations, and it plays a crucial role in facilitating the adoption of sustainable agricultural practices [11], [16]. According to institutional theory, supportive regulatory frameworks and policy incentives can significantly influence organizational behavior, including the adoption of environmentally friendly technologies [16], [35]. In Indonesia, various initiatives such as renewable energy subsidies and digital farming programs have been introduced to support sustainable agriculture, where institutional support not only directly

influences sustainability outcomes but also indirectly contributes by enhancing technological adoption. Thus, the following hypothesis is developed:

H4: Institutional support has a positive effect on agricultural sustainability outcomes.

2.6 *Renewable Energy, Precision Agriculture, and Market Access*

Beyond their direct effects on sustainability outcomes, renewable energy use and precision agriculture technology are also expected to improve market access [11], [36], as the adoption of renewable energy can reduce production costs and increase efficiency, enabling farmers to compete more effectively in the market, while precision agriculture enhances product quality, consistency, and operational efficiency, which are essential for meeting market standards and expanding distribution channels [37]–[39]. Therefore, the following hypotheses are proposed:

H5: Renewable energy use has a positive effect on market access.

H6: Precision agriculture technology has a positive effect on market access.

2.7 *The Role of Institutional Support in Enhancing Technology Adoption*

Institutional support is also expected to influence the adoption of renewable energy and precision agriculture technologies, as training programs, subsidies, and policy incentives provided by institutions can reduce barriers to innovation adoption and increase farmers' readiness to implement new technologies [12], [31]. This perspective aligns

with the Diffusion of Innovation Theory, which emphasizes the importance of external support in accelerating the adoption of technological innovations [12], [31]. Thus, the following hypotheses are formulated:

H7: Institutional support has a positive effect on renewable energy use.

H8: Institutional support has a positive effect on precision agriculture technology adoption.

2.8 *The Mediating Role of Market Access*

Market access is not only a direct determinant of sustainability outcomes but also acts as a mediating variable between technological adoption and sustainability, as renewable energy and precision agriculture can improve production efficiency and product quality, yet their impact on sustainability outcomes will be maximized only when farmers have access to markets that reward environmentally friendly products. Therefore, the following hypotheses are proposed:

H9: Market access mediates the relationship between renewable energy use and agricultural sustainability outcomes.

H10: Market access mediates the relationship between precision agriculture technology and agricultural sustainability outcomes.

3. METHODS

This study adopts a quantitative research approach with an explanatory design [40]. The primary objective is to test the proposed hypotheses and analyze both direct and indirect effects among variables using a statistically rigorous framework. Data were

collected through a survey of agricultural stakeholders in Indonesia, including farmers, agricultural entrepreneurs, and practitioners who are engaged in or familiar with environmentally friendly agricultural practices. A purposive sampling technique was employed based on specific criteria, namely: (1) active involvement in agricultural

activities, (2) knowledge or experience related to sustainable agriculture, renewable energy, or agricultural technology, and (3) willingness to participate in the study. A total of 185 valid responses were obtained respondents who are actively engaged in agricultural activities in Indonesia.

Table 1. Demographic Sample

Category	Classification	N	%
Gender	Male	115	62.2
	Female	70	37.8
Age	< 30 years	39	21.1
	30–40 years	59	31.9
	41–50 years	41	22.2
	> 50 years	46	24.9
Education Level	Primary School	33	17.8
	Secondary School	82	44.3
	Diploma	26	14.1
	Bachelor Degree	44	23.8
Farming Experience	< 5 years	31	16.8
	5–10 years	61	33.0
	11–20 years	52	28.1
	> 20 years	41	22.2
Renewable Energy Exposure	Yes	89	48.1
	No	96	51.9
Precision Agriculture Usage	Yes	107	57.8
	No	78	42.2

Source: Analysis Data (2026)

The table 1 shows that the sample is dominated by male respondents (62.2%) and individuals in the productive age range of 30–50 years (54.1%). Most respondents have a secondary education background (44.3%) and more than five years of farming experience (83.2%), indicating a relatively experienced and knowledgeable sample. Additionally, while renewable energy adoption remains moderate (48.1%), the use of precision agriculture technology is relatively higher (57.8%), reflecting a growing trend toward digital transformation in the agricultural sector.

The data were collected using a structured questionnaire distributed both online and offline, with measurement items adapted from established literature to ensure content validity. All constructs were measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5

(strongly agree), allowing for the assessment of respondents' perceptions. The study includes five latent constructs: Renewable Energy Use (RE), Precision Agriculture Technology (PA), Market Access (MA), Institutional Support (IS), and Agricultural Sustainability Outcomes (ASO). Each construct was operationalized using multiple indicators reflecting key dimensions, such as energy efficiency and renewable adoption (RE), digital tools and automation (PA), distribution access and pricing stability (MA), policy and institutional assistance (IS), and environmental, economic, and social performance (ASO).

Data analysis was conducted using Structural Equation Modeling based on Partial Least Squares (PLS-SEM) with SmartPLS 4 software. The analysis followed a two-stage approach, consisting of measurement model (outer model) and

structural model (inner model) evaluation [41]. The outer model assessment included tests of convergent validity (factor loadings > 0.70; AVE > 0.50), discriminant validity (Fornell-Larcker criterion and cross-loadings), multicollinearity (VIF < 5), and reliability (Cronbach's Alpha and Composite Reliability > 0.70). The inner model evaluation examined the structural relationships using path coefficients, coefficient of determination (R^2), effect size (f^2), and predictive relevance (Q^2). Hypothesis testing was performed using the bootstrapping procedure with a significance level of 5% ($p < 0.05$), enabling robust estimation of both direct and indirect effects within the proposed model.

4. RESULTS AND DISCUSSION

4.1 Measurement Model Evaluation (Outer Model)

Convergent validity was evaluated using outer loadings and the Average Variance Extracted (AVE), with all indicators exceeding the recommended threshold of 0.70 and all AVE values remaining above 0.50, indicating satisfactory convergent validity. Furthermore, reliability was confirmed as both Cronbach's Alpha and Composite Reliability values for all constructs exceeded 0.70, demonstrating strong internal consistency. In addition, multicollinearity was assessed using the Variance Inflation Factor (VIF), where all values were below the threshold of 5.0, confirming that multicollinearity is not a concern in this model.

Table 2. Measurement Model

Construct	Code	Loading	VIF	CA	CR	AVE
Renewable Energy (RE)	RE1	0.812	2.214	0.871	0.910	0.718
	RE2	0.845	2.378			
	RE3	0.864	2.441			
	RE4	0.828	2.296			
Precision Agriculture (PA)	PA1	0.801	2.105	0.854	0.898	0.689
	PA2	0.833	2.267			
	PA3	0.846	2.354			
	PA4	0.812	2.189			
Market Access (MA)	MA1	0.789	1.984	0.836	0.887	0.663
	MA2	0.822	2.156			
	MA3	0.841	2.231			
	MA4	0.792	2.074			
Institutional Support (IS)	IS1	0.818	2.221	0.865	0.904	0.701
	IS2	0.847	2.347			
	IS3	0.859	2.418			
	IS4	0.823	2.263			
Sustainability Outcomes (ASO)	ASO1	0.834	2.487	0.882	0.918	0.737
	ASO2	0.861	2.563			
	ASO3	0.879	2.689			
	ASO4	0.842	2.512			

Source: Analysis Data (2026)

Table 2 shows that all constructs meet the criteria for validity and reliability. Outer loadings (0.789–0.879) exceed 0.70 and AVE values (0.663–0.737) are above 0.50, confirming convergent validity. Reliability is also strong, with Cronbach's Alpha (0.836–

0.882) and Composite Reliability (0.887–0.918) above 0.70. Additionally, VIF values (1.984–2.689) are below 5.0, indicating no multicollinearity issues.

Discriminant validity was evaluated using the Fornell-Larcker criterion.

Table 3. Fornell-Larcker Criterion

Construct	RE	PA	MA	IS	ASO
RE	0.847				
PA	0.621	0.830			
MA	0.588	0.645	0.814		
IS	0.602	0.677	0.659	0.837	
ASO	0.691	0.702	0.668	0.721	0.858

Source: Analysis Data (2026)

Table 3 presents the Fornell-Larcker criterion results, showing that the square root of the AVE for each construct (diagonal values ranging from 0.814 to 0.858) is higher than the correlations with other constructs, indicating good discriminant validity. This means that each construct is empirically distinct and measures a unique concept within the model. Although some correlations among variables are moderately high, particularly between Institutional Support and Sustainability Outcomes (0.721), they remain below the corresponding AVE square roots, confirming that there is no issue of construct overlap. Overall, these results demonstrate that the model satisfies discriminant validity requirements and is suitable for further structural analysis.

4.2 Structural Model Evaluation (Inner Model)

The structural model (inner model) evaluation aims to examine the relationships between latent constructs and test the proposed hypotheses using SmartPLS 4. This evaluation includes assessing the coefficient of determination (R^2), effect size (f^2), predictive relevance (Q^2), and path coefficients obtained through bootstrapping. The R^2 values indicate the proportion of

variance in endogenous constructs explained by exogenous variables in the model. The results show that renewable energy ($R^2 = 0.432$) and precision agriculture ($R^2 = 0.458$) are explained at a moderate level by institutional support, while market access ($R^2 = 0.512$) is moderately explained by renewable energy and precision agriculture. Meanwhile, agricultural sustainability outcomes ($R^2 = 0.681$) are strongly explained by renewable energy, precision agriculture, market access, and institutional support.

These findings suggest that 43.2% of the variance in renewable energy and 45.8% in precision agriculture are influenced by institutional support, while 51.2% of market access is determined by technological factors. Furthermore, 68.1% of sustainability outcomes are explained by the integrated model, indicating strong explanatory power. This highlights that the combination of technological innovation, market mechanisms, and institutional support plays a significant role in driving sustainable agriculture. In addition, the effect size (f^2) analysis is used to evaluate the contribution of each exogenous variable to the R^2 values of the endogenous constructs.

Table 4. Effect Size (f^2)

Relationship	f^2	Effect Size
RE → ASO	0.142	Medium
PA → ASO	0.167	Medium
MA → ASO	0.121	Small-Medium
IS → ASO	0.189	Medium
IS → RE	0.432	Large
IS → PA	0.458	Large
RE → MA	0.214	Medium
PA → MA	0.236	Medium

Source: Analysis Data (2026)

Table 4 shows the effect size (f^2) results, indicating the relative contribution of

each exogenous variable to the endogenous constructs. Institutional support demonstrates the strongest influence, with a large effect on renewable energy ($f^2 = 0.432$) and precision agriculture ($f^2 = 0.458$), highlighting its critical role in driving technology adoption. In terms of sustainability outcomes, institutional support ($f^2 = 0.189$), precision agriculture ($f^2 = 0.167$), and renewable energy ($f^2 = 0.142$) all exhibit medium effect sizes, suggesting that these factors play meaningful roles in improving sustainability performance. Market access

shows a small-to-medium effect ($f^2 = 0.121$) on sustainability outcomes, indicating a supportive but less dominant influence. Additionally, renewable energy ($f^2 = 0.214$) and precision agriculture ($f^2 = 0.236$) have medium effects on market access, confirming that technological adoption contributes to improving farmers' access to markets. Predictive relevance (Q^2) was assessed using the blindfolding procedure. A Q^2 value greater than zero indicates that the model has predictive relevance.

Table 5. Predictive Relevance (Q^2)

Endogenous Variable	Q^2	Interpretation
Renewable Energy (RE)	0.291	Predictive relevance
Precision Agriculture (PA)	0.307	Predictive relevance
Market Access (MA)	0.338	Predictive relevance
Sustainability Outcomes (ASO)	0.421	Strong predictive relevance

Source: Analysis Data (2026)

Table 5 presents the predictive relevance (Q^2) results, indicating that all endogenous constructs have Q^2 values greater than zero, which confirms that the model has adequate predictive capability. Renewable energy ($Q^2 = 0.291$), precision agriculture ($Q^2 = 0.307$), and market access ($Q^2 = 0.338$) demonstrate good predictive relevance, while sustainability outcomes show a higher value

($Q^2 = 0.421$), indicating strong predictive relevance. These findings suggest that the model is not only explanatory but also has strong predictive power, particularly in estimating agricultural sustainability outcomes based on the interaction of technological, market, and institutional factors.

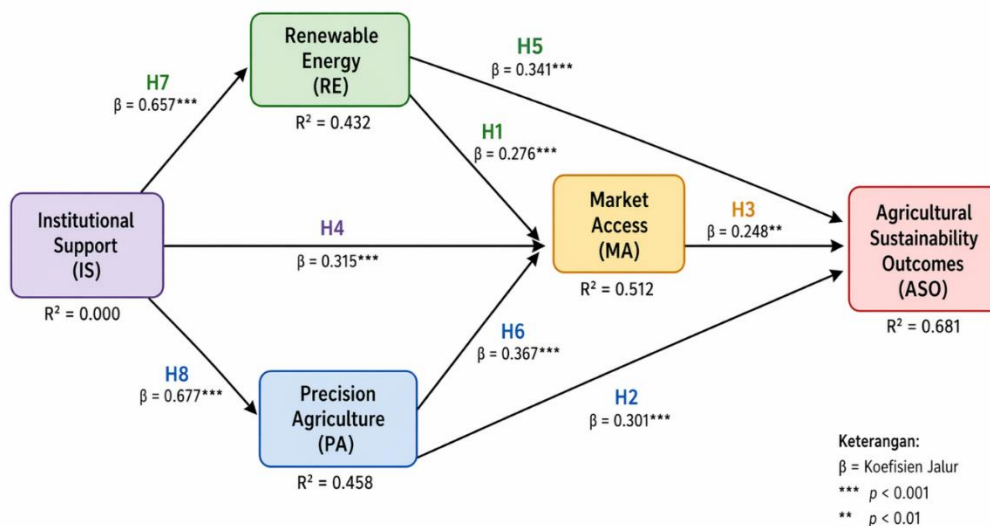


Figure 1. Hypothesis Testing

Source: Analysis Data (2026)

Hypothesis testing was conducted using the bootstrapping method with a significance level of 5% ($p < 0.05$).

Table 6. Path Coefficients and Hypothesis Testing

Hypothesis	Relationship	Coefficient (β)	T-Statistic	P-Value	Result
H1	RE \rightarrow ASO	0.276	3.214	0.001	Supported
H2	PA \rightarrow ASO	0.301	3.678	0.000	Supported
H3	MA \rightarrow ASO	0.248	2.987	0.003	Supported
H4	IS \rightarrow ASO	0.315	3.945	0.000	Supported
H5	RE \rightarrow MA	0.341	3.556	0.000	Supported
H6	PA \rightarrow MA	0.367	3.882	0.000	Supported
H7	IS \rightarrow RE	0.657	8.112	0.000	Supported
H8	IS \rightarrow PA	0.677	8.459	0.000	Supported

Source: Analysis Data (2026)

Table 6 presents the path coefficients and hypothesis testing results, showing that all proposed relationships are positive and statistically significant ($p < 0.05$), thus supporting all hypotheses. Institutional support emerges as the strongest driver of technology adoption, with substantial effects on renewable energy ($\beta = 0.657$) and precision agriculture ($\beta = 0.677$), indicating its critical role in facilitating innovation in agriculture. In terms of sustainability outcomes, institutional support ($\beta = 0.315$), precision agriculture ($\beta = 0.301$), renewable energy ($\beta = 0.276$), and market access ($\beta = 0.248$) all demonstrate significant positive effects, highlighting the importance of integrating technological,

economic, and institutional factors. Furthermore, renewable energy ($\beta = 0.341$) and precision agriculture ($\beta = 0.367$) significantly influence market access, suggesting that technological improvements enhance farmers' competitiveness and ability to reach broader markets. Overall, these results confirm the robustness of the proposed model and emphasize the interconnected roles of institutional support, technology adoption, and market mechanisms in driving agricultural sustainability.

To examine the mediating role of market access, indirect effects were analyzed.

Table 7. Indirect Effects (Mediation Analysis)

Hypothesis	Indirect Path	Coefficient (β)	T-Statistic	P-Value	Result
H9	RE \rightarrow MA \rightarrow ASO	0.112	2.145	0.032	Supported
H10	PA \rightarrow MA \rightarrow ASO	0.128	2.367	0.018	Supported

Source: Analysis Data (2026)

Table 7 presents the indirect effects, indicating that market access significantly mediates the relationship between renewable energy and sustainability outcomes ($\beta = 0.112$, $p = 0.032$) as well as between precision agriculture and sustainability outcomes ($\beta = 0.128$, $p = 0.018$). These results confirm that both mediation paths are statistically significant, suggesting partial mediation. This implies that while renewable energy and precision agriculture directly improve sustainability outcomes, their impact is further strengthened when supported by

improved market access. In other words, technological adoption enhances production efficiency and product quality, but the full benefits for sustainability can only be realized when farmers are able to access markets that provide economic value for sustainable products. Overall, these findings highlight the crucial role of market mechanisms in translating technological advancements into broader sustainability outcomes.

Discussion

This study provides robust empirical evidence on the transformation of environmentally friendly agriculture in Indonesia by integrating renewable energy, precision agriculture technology, market access, and institutional support within a single analytical framework. The findings confirm that sustainability outcomes are shaped by a complex interaction of technological, economic, and institutional factors, extending prior research that often examines these variables in isolation [11], [36]. This integrative perspective contributes to the growing body of literature emphasizing systemic approaches to agricultural sustainability in developing economies [7], [37], [42].

The significant role of renewable energy in improving sustainability outcomes supports the argument that energy transition is a critical component of sustainable agriculture. The adoption of solar and bioenergy technologies not only reduces greenhouse gas emissions but also enhances operational efficiency and cost-effectiveness. This finding is consistent with recent studies highlighting the role of decentralized renewable energy systems in rural agricultural transformation [24], [25]. In the Indonesian context, where energy infrastructure disparities persist, renewable energy adoption also strengthens resilience against energy insecurity, aligning with the broader sustainability transition literature [26], [27].

Precision agriculture technology also demonstrates a strong positive effect on sustainability outcomes, reinforcing the importance of digital transformation in agriculture. The findings align with the smart farming paradigm, where data-driven decision-making improves input efficiency and reduces environmental externalities [28], [29]. From a theoretical standpoint, this supports the Resource-Based View (RBV), suggesting that digital capabilities act as strategic resources that enhance performance and sustainability [30], [38], [43]. This result also reflects the global trend toward Agriculture 4.0, where technological

innovation becomes a key driver of competitiveness and sustainability [28], [44].

Market access is found to be a significant determinant of sustainability outcomes, highlighting that sustainability is not only production-oriented but also market-driven. This finding supports the concept of demand-driven sustainability, where consumer preferences for environmentally friendly products incentivize producers to adopt sustainable practices [3], [45]. In developing countries such as Indonesia, improving market access through digital platforms and value chain integration is essential to ensure that sustainability translates into economic benefits [31], [46].

Institutional support emerges as the most influential factor, significantly affecting both sustainability outcomes and technology adoption. This finding reinforces institutional theory, which emphasizes the role of governance, policy frameworks, and regulatory environments in shaping innovation adoption [11], [16]. Empirical studies also confirm that government support, extension services, and financial incentives are key enablers of sustainable agricultural transformation [16], [35]. In Indonesia, the uneven implementation of such policies suggests the need for stronger institutional coordination and localized policy design.

Finally, the mediation analysis reveals that market access plays a crucial intermediary role between technological adoption and sustainability outcomes. This finding extends prior research by demonstrating that the benefits of technological innovation are amplified when supported by efficient market systems [11], [12]. It suggests that sustainability transformation requires not only technological advancement but also structural improvements in market systems. Therefore, this study proposes a holistic framework in which sustainability outcomes are achieved through the synergy of technology, market access, and institutional support.

Theoretical Contribution & Novelty

This study offers several important contributions to the literature by developing

an integrated model that simultaneously examines renewable energy, precision agriculture, market access, and institutional support, thereby addressing a significant gap in prior studies that tend to analyze these factors independently. It also extends the application of SEM-PLS in agricultural sustainability research, particularly within the context of developing countries with relatively small sample sizes, and introduces a mediated structural relationship that demonstrates the critical role of market access as a mechanism through which technological adoption translates into sustainability outcomes. In terms of novelty, this research uniquely combines energy transition and digital agriculture within a single framework, positions market access as a mediating variable, empirically validates institutional support as the strongest driver, and provides evidence from Indonesia as an under-researched context. Thus, this study advances both theoretical and empirical understanding of sustainable agriculture transformation.

Practical Implications

The findings of this study provide important implications for policymakers, practitioners, and stakeholders. Governments should prioritize investment in renewable energy and digital agriculture technologies, especially in rural areas, while also improving market access through digital platforms and supply chain integration to enhance farmers' economic benefits. Strengthening institutional support—such as subsidies, training, and extension services—is essential to accelerate technology adoption and ensure long-term sustainability. Additionally, practitioners are encouraged to adopt integrated strategies that combine technology and market orientation, while investors and development agencies should focus on supporting comprehensive agricultural ecosystems rather than isolated interventions.

Limitations and Future Research

Despite its contributions, this study has several limitations. First, the sample size is relatively limited (185 respondents), which may affect the generalizability of the findings

across all regions in Indonesia. Second, the use of self-reported data may introduce potential bias in measuring respondents' perceptions. Third, the cross-sectional design restricts the ability to capture dynamic changes over time. Therefore, future research is recommended to use larger and more diverse samples across regions or countries, apply longitudinal approaches to better understand sustainability transformation over time, incorporate additional variables such as financial inclusion, environmental awareness, and policy effectiveness, and explore multi-group analysis (MGA) to compare different farmer segments.

5. CONCLUSION

This study confirms that the transformation toward environmentally friendly agriculture in Indonesia is significantly influenced by the integration of renewable energy use, precision agriculture technology, market access, and institutional support. All variables examined show positive and significant effects on agricultural sustainability outcomes, highlighting the importance of a multidimensional approach in achieving sustainable agricultural systems. Institutional support emerges as the most critical driver, not only directly influencing sustainability outcomes but also facilitating the adoption of renewable energy and precision agriculture technologies. This underscores the essential role of government policies, training programs, and financial assistance in accelerating agricultural transformation. Additionally, market access is found to play both a direct and mediating role, indicating that technological advancements must be supported by effective market systems to maximize their impact.

The study also demonstrates that the model has strong explanatory power, suggesting that the interaction between technological innovation, economic mechanisms, and institutional frameworks is key to achieving sustainability in agriculture. These findings imply that efforts to promote environmentally friendly agriculture should be integrated rather than fragmented across

multiple dimensions. From a practical perspective, policymakers should prioritize strengthening institutional support, expanding access to renewable energy and digital technologies, and improving market infrastructure to ensure that farmers can fully benefit from sustainable practices. Future research is encouraged to use larger samples, explore different regional contexts, and

incorporate additional variables such as environmental awareness and financial inclusion. Overall, sustainable agriculture in Indonesia can be effectively achieved through a comprehensive strategy that combines innovation, market development, and strong institutional support, ensuring long-term environmental, economic, and social benefits.

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